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Prediction of effective through-thickness thermal conductivity of woven fabric reinforced composites with embedded particles

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ABSTRACT

A detailed three dimensional finite element model is used to predict the through-thickness thermal conductivity of a composite consisting of a woven fabric and matrix and compared with existing analytical two component models. It is found that Pilling's constitutive model for two phase system agrees well with the numerical predictions. Then uniformly or randomly distributed conductive particles are introduced in the matrix and the effective thermal conductivity of this three-phase system is evaluated numerically. A unified hybrid constitutive model is proposed for the through-thickness thermal conductivity prediction for the particle embedded woven fabric system, incorporating a combination of generalized rule of mixtures and Pilling model to address a wide range of particle volumes and particle and fiber thermal conductivities. The proposed model can be used as a simple guideline to estimate the through-thickness thermal conductivity of such three component composite structures with woven fabrics, particles and matrices.

1. Introduction

Use of textile architecture in composites has gained ground in the last decade [1–3]. Two dimensional woven fabrics [4,5] are commonly employed in composite structures because of their light weight, low fabrication costs, ease of handling, high adaptability and tailorability. Different types of fibers, including carbon, glass, aramid and various matrix materials have been used to create these heterogeneous composite laminates for different applications. Also, different stitching patterns (e.g. weaving, braiding, knitting [6]) for fabrics can be employed to tailor the composite physical and mechanical properties. The fiber diameter, arrangement and material characteristics play an important role in influencing the properties of the composite. The matrix material in the composite could also play a dominant role in defining some of the composite properties. Over the last few decades, predictive models have been developed to find effective properties of the composites based on its constituent materials and their properties.

Predictive models to find effective properties of a composite material range from very simple weighted average of the constituent material properties such as the rule of mixtures to very complicated formulations that account for spatial and orientation variation of the fibers in the system [7–10]. The effective properties have also been determined using numerical methods which can address the specifics of the geometry [11–14].

Effective properties determined from an analytic constitutive relationship can be readily used in stress, thermal or electrical analysis of the composite and hence are very desirable. In this work, we will focus on through-thickness thermal conductivity prediction of woven fabric with particle loaded polymer matrix. Currently there is no closed form equation that can accurately describe the effective through thickness thermal conductivity of the composite, given the thermal conductivity of the fibers, matrix and particles over a range of fiber and particle volume fractions. Our approach is to predict effective thermal conductivity using very detailed finite element models of a unit cell that represent the fiber-shape geometry, with a range of particle and fiber thermal conductivities and volume fractions. The results are compared with existing analytic models. A new unified hybrid constitutive model is presented to predict the effective through-thickness thermal conductivity of a three-constituent (fiber, matrix and particles) heterogeneous system. The goal was to show that the "unified hybrid constitutive model" that is an expression to describe three phase composite systems developed in this work is a reasonable

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approximation to predicting the effective thermal conductive of such composites. This is done by first validating by mesh refinement the results from FE simulation of three phase systems and then comparing the results of FE predictions with the new unified hybrid constitutive model for the two cases with different particle volume fractions. The results of the parametric study are evaluated to provide a design guideline in terms of constituent properties and woven parameters for material selection and design.

2. 3D geometric model generation

The effective through-thickness thermal conductivity of woven fabric is highly dependent on the constituent properties and the reinforcement architecture. Addressing the fabric geometry in microscopic detail will influence the effective properties of the composite. It is important to mesh the 3D geometric model to describe the fiber continuity and undulation without simplifying the architecture. Sheng and Hoa's approach [15] was adopted and weft and warp yarns were assumed to have elliptical cross sections as shown in Fig. 1.

The central path of the fiber crimp is taken to be a repetitive combination of elliptical segment kJ and rectilinear segment JM to simplify fiber spatial orientation. Here the fabric misalignment caused due to processing factors during manufacturing is ignored.

The undulated segment kJ of the yarn is described by elliptical equation

$$\frac{(x-m)^2}{w^2}+\frac{(y-n)^2}{t^2}=\frac{1}{4}, \quad (J_{lx}\leqslant x\leqslant J_{rx}) \tag{1}$$

where m, n represent the central coordinates of the cross section of the yarn on the XY plane; J_{lx}, J_{rx} are the x coordinates of the two tangent points of woven yarns; w, t represent the major axis (width) and minor axis (thickness) of the fabric cross section, respectively. The rectilinear segment JM of the yarn between two elliptical segments is given by a linear equation

$$y = kx + d, \quad (J_{rx}\leqslant x\leqslant M_x) \tag{2}$$

where k is the slope of the rectilinear segment JM, d is a constant and M is the center point of the linear path.

The coordinates of the tangent point J connecting elliptical segment and linear segment can be written as

$$J\left(m+E, n-t\sqrt{\frac{1}{4}-\frac{E^2}{w^2}}\right) \tag{3}$$

Thus the slope of the segment JM is determined by the two points J, M as

$$k_{JM}=\frac{M_y-J_y}{M_x-J_x} \tag{4}$$

Also from the elliptical Eq. (1), the slope of the tangent line at the point J can be expressed as:

$$k_{JM}=\left.\frac{dy}{dx}\right|_{x=m+T}=\frac{Em/w^2}{\sqrt{\frac{1}{4}-\frac{E^2}{w^2}}} \tag{5}$$

By combining the above Eqs. (4) and (5), the distance E (as depicted in Fig. 1, E represents the x coordinate difference of K and J) and the slope of the segment JM can be calculated. An arbitrary distance $t_d = w/10$ is designated as the distance from the yarn to the bottom and top surface of the model.

The three dimensional geometry of the reinforcing fabric for a woven fabric composite can be fully described by the previously defined geometric parameters and the spatial orientation of the yarn. In this paper, the fiber volume fraction is varied by changing the cross sectional area of the yarns and the thickness b of the cell while maintaining the ratio $w/t = 2$, and the unit cell width and length equal to a. The $w/t = 2$ ratio is used to represent the cross section shape as an ellipse, which is a good approximation for to represent the shape of fiber bundles as reported by many studies on fiber bundle shapes, although the exact aspect ratio can vary for different materials and different weave patterns. With the above general approach, 3D finite element model of the geometric arrangement shown in Fig. 2 can be generated for further analysis. This approach also makes it easier to study other geometric parameters of the yarns and their influence on the effective composite property. A view of the 3D model with a cross section at the center of one yarn is shown in Fig. 2.

A series of 3D fabric models were generated and meshed using ANSYS software as the tool of Finite Element Analysis with formulated macros scripted using Mechanical APDL. The element type used for the geometry mesh is SOLID70 which is a 3-D thermal solid element which has eight nodes with a single degree of freedom, which is the temperature at each node. The curved shape for the yarn undulation was approximated by piecewise line segments for the ease of line generation, hence there is a small gap of width equal to $w/40$ to avoid yarn overlapping. The gap distance was selected to ensure that is was small enough not to affect the volume fraction of fiber and large enough to not cause convergence problems.

The ANSYS analysis code solves the steady state heat diffusion equation to evaluate the temperature field at each node. Each element is assigned a thermal conductivity value of the fiber, matrix or particle. The boundary conditions prescribed are insulated along the four sides of the unit cell and constant temperature along the top and the bottom face (T_1 and T_2 respectively). For many repetitive cells at the interface between two cells the heat flow is balanced in the plane due to the repetitive feature in the plane which is represented by the insulated boundary condition. Once the temperature field is evaluated, the heat flux q, which should be the same along the top and bottom face are calculated by integrating the heat flux

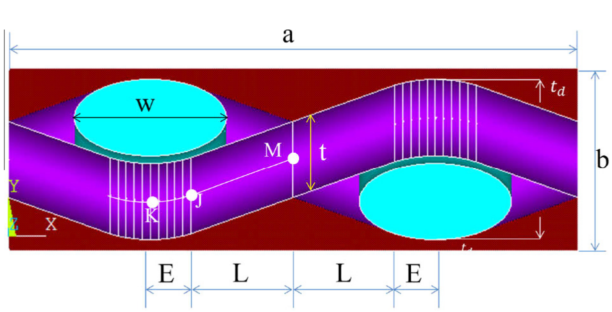

Fig. 1. Unit cell model of interlaced yarns in the woven fabric composite with geometric characteristic parameters.

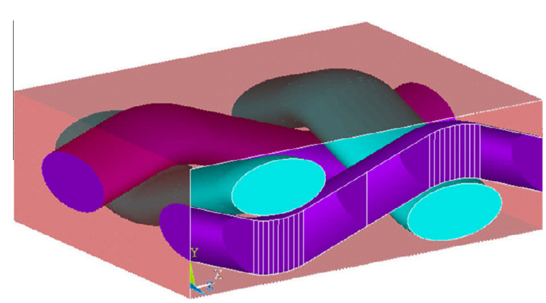

Fig. 2. Schematic of the 3D fabric model with fabric volume fraction of 34.91%.